ACE Aerosol STM and Relationship to PACE, etc.

Outline

- Revisit ACE Aerosol-Related Questions/Objectives
- PACE capabilities and limitations regarding ACE aerosol science objectives
- Capabilities/requirements of current and potential PACE and ACE aerosol measurements
- Future Aerosol-Relevant Satellite Sensors
- Recommendations

ACE Aerosol-Cloud-Ocean Ecosystem Aerosol-Related Science Questions and Objectives

- Sources, Processes, Transport and Sinks (SPTS)
- Direct Aerosol Radiative Forcing/Effects (DARF/DARE)
- Cloud-Aerosol Interaction (CAI)
- Aerosol-Ocean Ecosystems

Sources, Processes, Transport, and Sinks (SPTS) Questions/Objectives

- What are the global and regional aerosol sources and mass budget?
- What are the impacts of significant aerosol events on the local, regional and global aerosol burden and air quality?

  - Provide a quantitative, measurement-based estimate of aerosol source, sink and transport characteristics.
  - Estimate the aerosol contribution to the fertilization of land- and ocean-based ecosystems.
  - Characterize particulate matter (PM) concentrations on the ground from satellite observations.
  - Characterize and quantify major aerosol events, and estimate the contribution of these events to the total aerosol burden of the atmosphere.

Direct Aerosol Radiative Forcing/Effects (DARF/DARE) Questions/Objectives

- What is the direct aerosol radiative effect at the top-of-atmosphere, within-atmosphere and at the surface?
- What is the aerosol radiative heating of the atmosphere, and its impacts on cloud development?
  - Provide a firmer basis for measurement-based estimates of global and regional DARF at the top of atmosphere and its uncertainties by confronting issues not properly addressed by observations in the past.
  - Provide the first ever measurement-based estimate of the global direct aerosol radiative forcing at the bottom of the atmosphere to within ± 1 W/m^2, equivalent to estimating the global evaporation rate at the surface of ± 1 mm/month (~ 1% of global rates)
  - Provide vertically resolved, measurement-based estimates of the aerosol radiative heating of the atmosphere at an accuracy of ± 0.25 ^{o}K/day for 1.5 km layers.

Cloud-Aerosol Interaction (CAI) Questions/Objectives

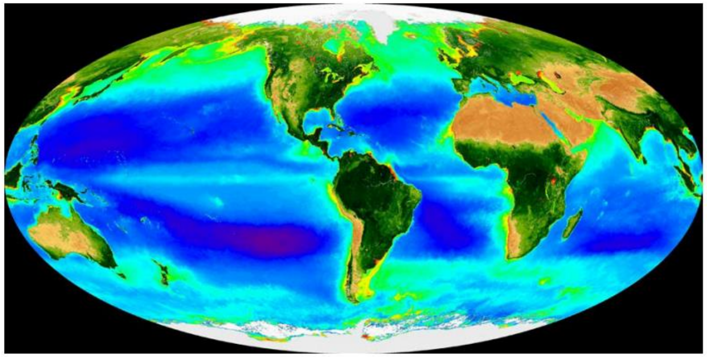
- How do aerosols affect cloud micro- and macro-physical properties, the subsequent radiative balance at the top, within and bottom of the atmosphere, and the water cycle?
- Where and what clouds, under which environmental conditions, are most susceptible to aerosol modifications?
- How do clouds and precipitation affect aerosol concentrations?
  - Provide strong constraints on estimates of the sensitivity of cloud radiative forcing and precipitation to aerosol number density via droplet and crystal nucleation.
  - Provide strong constraints on estimates of the sensitivity of cloud radiative forcing and precipitation to solar absorption by aerosol.
  - Provide strong constraints on the influence of clouds on the vertical distributions of aerosol physical and optical properties.
  - Understand the processes and thresholds controlling the rapid transition from a polluted non-precipitating airmass to a clean precipitating airmass.

Aerosol-Ocean Ecosystems-Cloud Interactions

- What are the physiochemical characteristics, temporal and spatial distributions, and source of aerosols deposited in oceans?
- How are the physical and chemical characteristics of deposited aerosols transformed in the atmosphere?
- How do ocean biological and photochemical processes affect the atmosphere and earth system?
- What is the number concentration, size distribution, chemical composition, and CCN properties of sea spray aerosols?
  - Identify microphysical and optical properties of aerosols, partition natural and anthropogenic sources, and characterize spectral complex index of refraction and particle size distribution
  - Characterize dust aerosols, their column mass, iron content and other trace elements, and their regional-to-global scale transport and flux from events to the annual cycle
  - Detect and quantify the imprint of oceanic biological processes on the optical and radiative properties of the overlying aerosols and clouds

What are capabilities and limitations of (PACE) regarding ACE aerosol science objectives?

Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) Mission Science Definition Team Report



October 16, 2012

Possible PACE Options in PACE SDT Report

Name	Ocean Color Instrument	Polarimeter	Aerosol Capabilities	Science Questions
OCI	Single view angle ocean color hyperspectral instrument with 350-800 nm range, plus UV channel (350 nm), 2 NIR channels (865, 820 nm) , and 3 SWIR channels (1.24, 1.64, 2.13). Spatial resolution of 1 km^2, two day global coverage	None	Aerosol somewhat like MODIS and VIIRS, clouds less than MODIS and VIIRS	Heritage aerosol
OCI/OG	Same as OCI, plus 500 m^2 spatial resolution, oxygen-A band, one day global coverage, hyperspectral coverage over 800-900 nm	None	Aerosol somewhat like MODIS and VIIRS, clouds less than MODIS and VIIRS, aerosol height for atmospheric correction	Heritage aerosol
OCI+	Same as OCI, plus 3 additional SWIR bands (0.94, 1.38, 2.25 um)	None	Aerosol and clouds similar to MODIS	Heritage aerosol and cloud
OCI/A	Same as OCI+, 250 m spatial resolution	None	Aerosol and clouds similar to MODIS, improved resolution for aerosols near clouds	Aerosol impacts on PBL liquid clouds
OCI-3M	Same as OCI	3MI: POLDER heritage, 12 channel (410-2130 nm), 14 view angle, polarimetrically sensitive imager	Improved aerosol AOD, size, type, SSA refractive index	Aerosol transport, limited radiative forcing
OCI/A-3M	Same as OCI+, 250 m spatial resolution	3MI: POLDER heritage, 12 channel (410-2130 nm), 14 view angle, polarimetrically sensitive imager	Improved aerosol AOD, size, type, SSA refractive index	Aerosol transport, limited radiative forcing, limited cloud impacts on aerosols

- PACE Configuration is Currently Unknown
- Several PACE Options for Ocean and Atmosphere Objectives Described in PACE SDT Report
- Examined OCI and OCI-3MI options

Capabilities of current satellite instruments and potential PACE and ACE instruments regarding aerosol science objectives

- Instruments
  - Current: (MODIS/VIIRS/OMI; MISR) Instruments
  - Future:
    - PACE (Two options: OCI and OCI-3MI polarimeter)
    - ACE
- <u>Aerosol related Science Questions in PACE SDT Report</u>

Science Question/Objective	Required Aerosol + Cloud Parameters	MODIS/VIIRS/OMI	MISR	OCI[8]	OCI-3MI	ACE
"MODIS-Like" heritage aerosol products • What are long-term changes in AOD?	AOD, Angström exponent (water)	Yes	Yes	Yes	Yes	Yes
"POLDER/PARASOL/MISR" heritage aerosol products • What are long-term changes in AOD?	AOD, Angström exponent (water), qualitative aerosol type	No	Yes	No	Yes	Yes
How do aerosols affect PBL liquid cloud properties?	AOD, cloud properties	Some	Some	No	Some	Yes
How do clouds affect aerosol properties in regions near cloud boundaries?	<u>Column</u> AOD(λ), AAOD(l), m(l) (2 modes), r_{eff}, ν, Morphology, nonsphericity <u>Vertically Resolved</u> α, ω, r_{eff} <u>Cloud</u> OD, r_{eff}, ν, phase	No	No	No	Some	Yes
Atmospheric Correction for Ocean Color Retrievals	AOD(λ), AAOD(λ), aerosol height	Some	Some	Some	Yes	Yes

[8]OCI requirements state noon equator crossing (+/- 1 hour). Consequently some kind of gimbal mount will be required to view angles out of sun glint.

Capabilities of current and potential PACE and ACE regarding ACE SPTS and DARF Objectives

Science Question/Objective	Required Aerosol + Cloud Parameters	MODIS/VIIRS/OMI	MISR	OCI[8]	OCI-3MI	ACE
Sources, Processes, Transport and Sinks (SPTS) • What are the global and regional aerosol sources and mass budget?	Column AOD(λ), AAOD(λ), m(λ) (2 modes), r_{eff},ν, Morphology, nonsphericity Vertically Resolved α, r_{eff}	Limited[1]	Limited[1]	Limited[1]	Some	Yes (with imaging polarimeter + HSRL) [2]
• What are the impacts of significant aerosol events on the local, regional and global aerosol burden and air quality?	Column AOD(λ),m(λ) (2 modes), r_{eff},ν	Limited[1]	Limited[1]	Limited[1]	Yes	Yes
Direct Aerosol Radiative Forcing/Effects (DARF/DARE) • What is the direct aerosol radiative effect at the top-of-atmosphere, within-atmosphere and at the surface?	Column AOD(λ), AAOD(λ), m(λ) (2 modes), r_{eff},ν, Morphology, nonsphericity Vertically Resolved α, r_{eff} Surface BRDF/albedo	No	Limited[3]	No	Some	Yes (with polarimeter +HSRL)[4]
Direct Aerosol Radiative Forcing/Effects (DARF/DARE) • What is the aerosol radiative heating of the atmosphere, and its impacts on cloud development?	Column AOD(λ), AAOD(λ), m(λ) (2 modes), r_{eff},ν, Morphology, nonsphericity Vertically Resolved α, ω, r_{eff} Cloud OD, r_{eff}, ν, phase	No	No	No	No	Yes (with polarimeter +HSRL) for aerosol

[1] MODIS and MISR (and OCI) provide a limited amount of this information (e.g. AOD(λ) and MISR provides a measure of nonsphericity.

[2] Source sinks and mass budget required integration with aerosol assimilation models.

[3]MISR can provide some measure of surface BRDF/albedo

[4] While we may disagree, IPCC AR5 suggests TOA is quite good when models are combined with MODIS. That is certainly not the case for surface and within-atmospheric radiative forcing associated with aerosol absorption and why the group does not consider DARF to be a solved problem.

Capabilities of current and potential PACE and ACE regarding ACE CAI and Aerosol-Ocean Objectives

Science Question/Objective	Required Aerosol + Cloud Parameters	MODIS/VIIRS/OMI	MISR	OCI[8]	OCI-3MI	ACE
Cloud-Aerosol Interaction (CAI) • How do aerosols affect cloud micro- and macro-physical properties, the subsequent radiative balance at the top, within and bottom of the atmosphere, and the water cycle? • Where and what clouds, under which environmental conditions, are most susceptible to aerosol modifications? • How do clouds and precipitation affect aerosol concentrations?	Column AOD(λ),m(λ) (2 modes), r_{eff},ν, nonsphericity, N Vertically Resolved N_a, AAOD, r_{eff}, α, nonsphericity Cloud[9] OD, r_{eff}, ν, phase, LWP	No	No	No	Some	Yes (polarimeter +HSRL) [5]
Aerosol-Ocean • What are the physiochemical characteristics, temporal and spatial distributions, and source of aerosols deposited in oceans? • How are the physical and chemical characteristics of deposited aerosols transformed in the atmosphere? • What is the number concentration, size distribution, chemical composition, and CCN properties of sea spray aerosols?	Column AOD(λ), AAOD(λ), m(λ) (2 modes), r_{eff},ν, Morphology, nonsphericity Vertically Resolved α, r, N_a, AAOD, nonsphericity	No	No	No	Some (column properties)	ACE (imaging polarimeter+HSRL)[6,7]

[5]Addressing effects on precipitation and water cycle of aerosols implicitly suggestions the need for a radar.

[6]Should comment on whether iron availability is tied to dust absorption. Shape allows for tracking of dust, but availability of iron for fertilization is widely variable.

[7]Accuracy of remote CCN estimates and even more GCCN estimates are critical issues here that are really open issues for ACE that need to be addressed.

[9]Radar and microwave radiometer measurements are required for cloud base, and compliment cloud-top heights and LWP retrievals from other instruments.

Capabilities/requirements of current and potential PACE and ACE aerosol measurements

Capabilities/requirements of current and potential PACE and ACE aerosol measurements

In some cases, table entries are estimated (rather than demonstrated/validated) capabilities and so may be ambitious

Aerosol Measurement Capability	MODIS/VIIRS/OMI	MISR	OCI	OCI+3MI	ACE
Aerosol detection	Yes	Yes	Yes	Yes	Yes
Aerosol Effective Layer Altitude	No	Yes…if AOT is a few tenths and spatially well defined. Uncertainty ~ 0.5 km	Use of A-band implies crude estimate with uncertainty >0.5 km	Yes, with ~ 0.5 km uncertainty if AOT>0.2	Yes, with < 0.5 km uncertainty if AOT>0.2 (imager); Much higher resolution along lidar curtain
Aerosol Type	Limited information (FMF) over water	Qualitative information regarding size, shape, absorption	Limited information over water (FMF, some spectral absorption)	Yes (column average)	Yes (column average) and above clouds (req); vertically resolved along lidar curtain
Aerosol Effective Radius (Multiple Modes)	Limited information over water (total)	Qualitative (total)	Limited information over water (total)	10% (total) ~15% (fine) ~30% (coarse)	~10% (fine) ~10% (coarse); column average and above clouds; ~20% (vertically resolved) for α>50 Mm^{-1}
Effective variance	No	No	No	~20% (total) ~25% (fine) ~30% (coarse)	~50% (fine) ~50% (coarse); column averaged and above clouds
Fine Mode Fraction	Yes over water +/- 0.25%	Yes	Yes over water +/- 25%	Yes 10-25% over land 10-15% over water	Yes 10-15% over land 5-10% over water
Sphericity	No	Qualitatively	No	Fraction of spherical particles~10% (if Angstrom exponent <0.6)	Yes, spherical and nonspherical (column average and above clouds); vertically resolved along lidar curtain
Concentration	No	No	No	Volume <0.05 mm^3/mm^2	Number +/-100% Vertically resolved (500m in BL, 1.5 km in troposphere)

Capabilities/requirements of current and potential PACE and ACE aerosol measurements

In some cases, table entries are estimated (rather than demonstrated/validated) capabilities and so may be ambitious

Aerosol Measurement Capability	MODIS/VIIRS/OMI	MISR	OCI	OCI+3MI	ACE
Spectral Optical Depth	Yes (visible) Over land 0.05 and 15% (550 nm) Over water 0.03 and 15% (550 nm)	Yes (visible) Over land 0.05 or 15% (550 nm) Over water 0.03 or 15% (550 nm)	Yes (UV) 0.05 and 30% (visible) Over land 0.05 and 15% Over water 0.03 oand15%	Yes over land (VIS): 0.04 or 10% (total); 0.05 or 20% (coarse); 0.04 or 25% (fine); over ocean (VIS): 0.02 or 10% (total); 0.03 or 15% (coarse); 0.02 or 10% (fine);	over land: 0.04 or 10% (total); 0.04 or 15% (coarse); 0.04 or 15% (fine); over ocean: 0.02 or 5% (total); 0.02 or 10% (coarse); 0.02 or 10% (fine); ACE report states Larger of ±0.02 or ±0.05AOD
Absorption Optical Depth	Limited MODIS+OMI (0.05) for AOD > 0.2	Qualitative (AOD>0.2)	~+/-0.03-0.05	0.02-0.03 (spectral)	±0.02 (spectral, multiple modes) for AOD>0.1
Single Scattering Albedo	Limited MODIS+OMI (0.03-0.05) for AOD > 0.2	Qualitative (AOD>0.2)	~+/-0.03-0.05	over land (VIS): 0. 03($\tau \geq 0.4$) 0.05 ($0.1 \leq \tau < 0.4$) over ocean (VIS): 0. 03 ($\tau \geq 0.3$) 0.05 ($0.1 \leq \tau < 0.3$)	over land: (VIS) 0. 03 over ocean: (VIS) 0. 02 In 1.5 km layers in free troposphere; 500 m in BL
Real Refractive Index (spectral multiple modes)	No	No	No	over land (VIS): 0.03 (τ 440 ≥ ~0.5) over ocean (VIS): 0. 03 (τ 440 ≥ ~0.3) (spectral)	~±0.02 (spectral, modes) when AOD>0.1; column averaged and above clouds (req); vertically resolved (goal)

Future (near-term) Aerosol-Relevant Satellite Sensors

Future Aerosol-Relevant Satellite Sensors

- Cloud and Aerosol Transport System (CATS)
  - Launch ~Sept. 2014
  - Mounted on ISS
  - Lidar backscatter, depolarization at 532, 1064 nm
  - 355 nm backscatter, 532 nm HSRL capability (technology demonstration)
- Sentinel-5 Precursor with Tropospheric Monitoring Instrument (TROPOMI)
  - Launch ~Spring 2015
  - Fly in formation about 10 min behind NPP (824 km)
  - Updated version of OMI
  - Detect UV absorbing aerosols
  - Retrieve trace gases associated with pollution (sulfur dioxide, formaldehyde, carbon monoxide)
  - Oxygen A-band measurements help constrain aerosol layer height
  - Combination of VIIRS (on NPP) + TROPOMI has potential to improve on MODIS type aerosol measurements and represent a baseline for ACE mission to improve on

Future Aerosol-Relevant Satellite Sensors

- Atmospheric LIDar (ATLID) on EarthCARE
  - Launch ~fall 2016
  - Orbit altitude ~ 393 km
  - Lidar backscatter, depolarization, HSRL extinction
  - 355 nm only
- Multi-spectral Imager (MSI) on EarthCARE
  - Launch ~fall 2016
  - Radiometric imager
  - Swath of 150 km
  - Seven bands (shortest wavelength 670 nm) limits ability to combine lidar + imager for aerosol retrievals and precludes retrievals of aerosol absorption

Future Aerosol-Relevant Satellite Sensors

- Second Generation Global Land Imager (SGLI)
  - Launch ~end of 2015 on GCOM-Climate 1 satellite (~800 km)
  - High spatial resolution (250 m) from UV to SWIR allows methods developed for OMI and MODIS with additional spectral capabilities
  - Gimbaled polarimetric imager can look forward or aft 45 deg providing sensitivity to absorbing and nonabsorbing accumulation mode aerosols
  - Combination of polarized NIR and UV/blue/visible total radiance has potential to improve on existing MODIS capabilities, especially over land
- Geostationary
  - Advanced Baseline Imager (GOES-R)
    - Launch in 2016
    - Improved spectral and spatial coverage over GOES-N
  - Tropospheric Emissions: Monitoring of Pollution (TEMPO)
    - Launch ~2019
    - UV/visible coverage for trace gases and aerosols

Future Aerosol-Relevant Satellite Sensors

- Multi-directional, Multi-polarization, Multispectral Imaging Mission (3MI) on MetOp Second Generation satellite
  - Launch ~2020
  - 820 km orbit
  - 2200 km swath
  - UV to SWIR coverage
  - Moderate resolution (2-4 km)
  - Polarization over wide range of viewing angles
  - Should provide significant improvement over existing spaceborne aerosol retrievals

Recommendations

- Examine combined active (lidar)+ passive (polarimeter) retrieval algorithms to determine information content of various combinations of wavelengths, angles, etc.
- Revisit uncertainty estimates for complex index (and single scattering albedo) and size as a function of aerosol optical depth and aerosol type for different fine mode fractions.
- Evaluate ACE fine mode effective variance uncertainties given the scientific questions associated with being able to detect and characterize CCN. Examine role of HSRL 355 nm measurements in this role.
- For radiative forcing
  - Analyses focused on impact of measurements and measurement requirements for aerosol forcing
  - Address aerosol absorption as well as AOD
- Development/deployment of instrument(s) that can provide range resolved (e.g. via aircraft) measurement of ambient AAOD and SSA of sufficient accuracy (+/-0.01-0.02) to validate remote sensing absorption retrievals

Extra Slides

PACE Threshold Ocean Mission Requirements

λ	Band Width (nm)	Spatial Resol. (km^2)	L_{typ}	L_{max}	SNR-Spec
350	15	1	7.46	35.6	300
360	15	1	7.22	37.6	1000
385	15	1	6.11	38.1	1000
412	15	1	7.86	60.2	1000
425	15	1	6.95	58.5	1000
443	15	1	7.02	66.4	1000
460	15	1	6.83	72.4	1000
475	15	1	6.19	72.2	1000
490	15	1	5.31	68.6	1000
510	15	1	4.58	66.3	1000
532	15	1	3.92	65.1	1000
555	15	1	3.39	64.3	1000
583	15	1	2.81	62.4	1000
617	15	1	2.19	58.2	1000
640	10	1	1.90	56.4	1000
655	15	1	1.67	53.5	1000
665	10	1	1.60	53.6	1000
678	10	4	1.45	51.9	2000
710	15	1	1.19	48.9	1000
748	10	1	0.93	44.7	600
820	15	1	0.59	39.3	600
865	40	1	0.45	33.3	600
1240	20	1	0.088	15.8	250
1640	40	1	0.029	8.2	180
2130	50	1	0.008	2.2	15

Threshold Ocean Mission Requirements

Orbit	• sun-synchronous polar orbit • equatorial crossing time between 11:00 and 1:00 • orbit maintenance to ±10 minutes over mission lifetime
Global Coverage	• 2-day global coverage to solar zenith angle of 75° • mitigation of sun glint • multiple daily observations at high latitudes • view zenith angles not exceeding ±60° • mission lifetime of 5 years
Navigation and Registration	• pointing accuracy of 2 IFOV and knowledge equivalent to 0.1 IFOV over the full range of viewing geometries (e.g., scan and tilt angles) • pointing jitter of less than 0.01 IFOV between any adjacent spatial samples • spatial band-to-band registration of 80% of one IFOV between any two bands, without resampling • simultaneity of 0.02 second (to ensure co-registration of spectral bands to within 80% of one IFOV considering satellite along-track motion)
Instrument Performance Tracking	• characterization of all detectors and optical components through monthly lunar observations through Earth-viewing port • characterization of instrument performance changes to ±0.2% within the first 3 years and maintenance of this accuracy thereafter for the duration of the mission • monthly characterization of instrument spectral drift to an accuracy of 0.3 nm • daily measurement of dark current and observations of a calibration target/source, with knowledge of daily calibration source degradation to ~0.2%
Instrument Artifacts	• Prelaunch characterization of linearity, response versus view angle (RVVA), polarization sensitivity, radiometric and spectral temperature sensitivity, high contrast resolution, saturation, saturation recovery, crosstalk, radiometric and band-to-band stability, onboard calibrator performance (e.g., bidirectional reflectance distribution of a diffuser, etc.), and relative spectral response • prelaunch absolute calibration of 2% and on-orbit absolute calibration accuracy (before vicarious calibration) of better than 5% • overall instrument artifact contribution to TOA radiance of <0.5% after correction • image striping to < 0.1% in calibrated TOA radiances • crosstalk contribution to radiance uncertainties 0.1% at L_{typ} • polarization sensitivity of ≤1% and knowledge of polarization sensitivity to ≤ 0.2% • no detector saturation for any science measurement bands at L_{max} • RVVA of <5% for the entire view angle range and by <0.5% for view angles that differ by less than 1° • Stray light contamination for the instrument < 0.2% of L_{typ} 3 pixels away from a cloud • out-of-band contamination of <0.01 for all multispectral channels • radiance-to-counts relationship characterized to 0.1% over full dynamic range (from L_{typ} to L_{max})
Spatial Resolution	• Global spatial coverage of 1 km x 1 km (±0.1 km) along-track (nadir)
Atmospheric Corrections	• retrieval of $[\rho_w(\lambda)]_N$ for open-ocean, clear-water conditions and standard marine atmospheres with an accuracy of the maximum of either 5% or 0.001 over the wavelength range 400 – 710 nm • Two NIR atmospheric correction bands (865 nm and either 820 or 940 nm) • NUV band centered near 350 nm • SWIR bands centered at 1240, 1640, and 2130 nm
Science Spectral Bands	• 5 nm spectral resolution from 350 to 800 nm • complete ground station downlink and archival of 5 nm data
Signal-to-noise	• SNR at ocean L_{typ} of 1000 from 360 to 800 nm; 300 @ 350 nm; 600 @ NIR bands; 250, 180, and 15 @ 1240, 1640, & 2130 nm
Mission	• full reprocessing capability of all PACE data at a minimum frequency of 1 – 2 times annually • Integrated process studies, assessments, and cal/val studies • Three-hour data latency and direct broadcast of aggregate spectral bands • Robust data and results distribution system

PACE Ocean STM

PACE Threshold Ocean Mission Science Traceability Matrix (STM)

Science Questions	Approach	Maps to Science Question	Measurement Requirements	Platform Reqmts.	Other Needs
1 What are the standing stocks, compositions, and productivity of ocean ecosystems? How and why are they changing?	Quantify phytoplankton biomass, pigments, optical properties, key groups (functional/HABS), & estimate productivity using bio-optical models, chlorophyll fluorescence, & ancillary physical properties (e.g., SST, MLD)	1 4 2 5 3 6	• water leaving radiance at 5 nm resolution from 350 to 800 nm • 10 to 40 nm wide atmospheric correction bands at 350, 820 (or 940), 865, 1240, 1640, and 2130 nm • characterization of instrument performance changes to ±0.2% in first 3 years & for remaining duration of the mission • monthly characterization of instrument spectral drift to 0.3 nm accuracy • daily measurement of dark current & a calibration target/source with its degradation known to ~0.2% • Prelaunch characterization of linearity, RVVA, polarization sensitivity, radiometric & spectral temperature sensitivity, high contrast resolution, saturation, saturation recovery, crosstalk, radiometric & band-to-band stability, bidirectional reflectance distribution, & relative spectral response • overall instrument artifact contribution to TOA radiance of < 0.5% • image striping to < 0.1% in calibrated top-of-atmosphere radiances • crosstalk contribution to radiance uncertainties of 0.1% at L_{typ} • polarization sensitivity ≤ 1% • knowledge of polarization sensitivity to ≤ 0.2% • no detector saturation for any science measurement bands at L_{max} • RVVA of < 5% for entire view angle range & < 0.5% for view angles differing by less than 1° • Stray light contamination for the instrument < 0.2% of L_{typ} 3 pixels away from a cloud • Out-of-band contamination < 0.01 for all multispectral channels • Radiance-to-counts characterized to 0.1% over full dynamic range • Global spatial coverage of 1 km x 1 km (±0.1 km) along-track • Multiple daily observations at high latitudes • View zenith angles not exceeding ±60° • Standard marine atmosphere, clear-water $[r_w(l)]_N$ retrieval with accuracy of max[5% , 0.001] over the wavelength range 400 – 710 nm • SNR at L_{typ} for 1 km² aggregate bands of 1000 from 360 to 710 nm; 300 @ 350 nm; 600 @ NIR bands; 250, 180, and 15 @ 1240, 1640, & 2130 nm • Absolute calibration to 2% pre-launch and 5% on-orbit (before vicarious calibration) • 3 hour data latency and direct broadcast of aggregate spectral bands • Simultaneity of 0.02 second	2-day global coverage to solar zenith angle of 75° Sun-synchronous polar orbit with equatorial crossing time between 11:00 and 1:00 Maintain orbit to ±10 minutes over mission lifetime Mitigation of sun glint Mission lifetime of 5 years Storage and download of full spectral and spatial data Monthly lunar observations at constant phase angle through Earth observing port System-level pointing accuracy of 2 IFOV and knowledge equivalent to 0.1 IFOV over the full range of viewing geometries System-level pointing jitter accuracy of 0.01 IFOV or less between any adjacent spatial samples Spatial band-to-band registration of 80% of one IFOV between any two bands, without resampling	Capability to reprocess full data set 1 – 2 times annually *Ancillary data sets from models missions, or field observations*: Measurement Requirements (1) Ozone (2) Water vapor (3) Surface wind velocity and barometric pressure (4) NO_2 Science Requirements (1) SST (2) SSH (3) PAR (4) UV (5) MLD (6) CO_2 (7) pH (8) Ocean circulation (9) Aerosol deposition (10) run-off loading in coastal zone
2 How and why are ocean biogeochemical cycles changing? How do they influence the Earth system?	Measure particulate &dissolved carbon pools, their characteristics & optical properties	2 3			
3 What are the material exchanges between land & ocean? How do they influence coastal ecosystems and biogeochemistry? How are they changing?	Quantify ocean photobiochemical & photobiological processes	2 4			
4 How do aerosols influence ocean ecosystems & biogeochemical cycles? How do ocean biological & photochemical processes affect the atmosphere?	Estimate particle abundance, size distribution (PSD), & characteristics	1 3			
5 How do physical ocean processes affect ocean ecosystems & biogeochemistry? How do ocean biological processes influence ocean physics?	Assimilate PACE observations in ocean biogeochemical model fields to evaluate key properties (e.g., air-sea CO_2 flux, carbon export, pH, etc.)	2 4			
6 What is the distribution of both harmful and beneficial algal blooms and how is their appearance and demise related to environmental forcings? How are these events changing?	Compare PACE observations with field- and model data of biological properties, land-ocean exchange, physical properties (e.g., winds, SST, SSH), and circulation (ML dynamics, horizontal divergence, etc)	3 4 5 6			
7 How do changes in critical ocean ecosystem services affect human health and welfare? How do human activities affect ocean ecosystems and the services they provide? What science-based management strategies need to be implemented to sustain our health and well-being?	Combine PACE ocean & atmosphere observations with models to evaluate ecosystem-atmosphere interactions	4	**Implementation Requirements** ***Vicarious Calibration***: Ground-based R_{rs} data for evaluating post-launch instrument gains. Features: (1) Spectral range = 350 - 900 nm at ≤ 3 nm resolution, (2) Spectral accuracies ≤ 5%, (3) Spectral stability ≤ 1%, (4) Deploy = 1 yr prelaunch through mission lifetime, (5) Gain standard errors to ≤ 0.2% in 1 yr post-launch, (6) Maintenance & deploy centrally organized, & (7) Routine field campaigns to verify data quality & evaluate uncertainties ***Product Validation***: Field radiometric & biogeochemical data over broad possible dynamic range to evaluate PACE science products. Features: (1) Competed & revolving Ocean Science Teams, (2) PACE-supported field campaigns (2 per year), (3) Permanent/public archive with all supporting data		
	Assess ocean radiant heating and feedbacks	5			
	Conduct field sea-truth measurements & modeling to validate retrievals from the pelagic to near-shore environments	1 4 2 5 3 6			
	Link science, operational, & resource management communities. Communicate social, economic, & management impacts of PACE science. Implement strong education & capacity building programs.	7	**Ocean Biogeochemistry-Ecosystem Modeling** • Expand model capabilities by assimilating expanded PACE retrieved properties, such as NPP, IOPs, & phytoplankton groups & PSD's • Extend PACE science to key fluxes: e.g., export, CO_2, land-ocean exchange		

Review - ACE Science Traceability Matrix

Sources, Processes, Transport, Sinks (SPTS)

Direct Aerosol Radiative Forcing (DARF)

Science Questions	Geophysical Parameters	Measurement Requirements	Mission Requirements
(1) What are the key sources, sinks and transport paths of airborne sulfate, organic, black carbon, sea salt and mineral dust aerosol? (2) What is the impact of specific significant aerosol events such as volcanic eruptions, wild fires, dust outbreaks, urban/industrial pollution etc. on the local, regional and global aerosol burden?	Column: - $\tau_a(\lambda)$ - $\tau_{a\text{-}abs}(\lambda)$ - $m_a(\lambda)$ (2 modes) - $r_{eff,a}$ (2 modes) - $v_{eff,a}$ (2 modes) -morphology Vertically resolved: -extinction - $\tau_{a\text{-}abs}(\lambda)$ - $m_a(\lambda)$ - $r_{eff,a}$ - $v_{eff,a}$ -morphology Cloud Top for (3) and (4) only: - τ_c - $r_{eff,c}$ - $v_{eff,c}$ - thermo-dynamic phase Definitions and accuracy requirements in Appendix	High Resolution Spectral Lidar (HSRL): -backscatter 355 nm, 532 nm, 1064 nm -extinction 355nm, 532 nm - backscatter 100m vertical 100m along track - depol in 2 channels Imaging polarimeter: -minimum 6 to 8 wavelengths spanning either UV or 410 nm to either 1630 nm or 2250 nm. - Multiangle TBD, range ±50° at spacecraft - polarization accuracy 0.5% - combination polarized and non-polarized channels possible - resolution 250 m in at least one channel -swath 2-day coverage for (1) and (2) -swath ~400 km for (3) and (4) Instrument designs must demonstrate attainment of Geophysical Parameter accuracies in Appendix Measurement requirement details in Appendix	Integrated satellite, sub-orbital and modeling approach required to meet science obectives. Required ancillary data: - land surface albedo map - ground network $\tau_a(\lambda)$, shortwave and longwave F_d and F_{net} - ground and airborne: column and vertically resolved $\tau_a(\lambda)$, $\tau_{a\text{-}abs}(\lambda)$, $m_a(\lambda)$ (2 modes), $r_{eff,a}$ (2 modes), $v_{eff,a}$ (2 modes), morphology, $P_{a\text{-}pol}(\Theta)$ - space measurements: Top of atmosphere shortwave and long wave F_u, collocated T(z), q(z), V(z), fire strength, frequency and location orange for (1) or (2) only blue for (3) or (4) only black for both
(3)What is the direct aerosol radiative forcing (DARF) at the top-of-atmosphere, within-atmosphere and at the surface? (4) What is the aerosol radiative heating of the atmosphere due to absorbing aerosols, and how will this heating affect cloud development and precipitation processes?			

ACE Draft Report

Review - ACE Science Traceability Matrix

Cloud-Aerosol Interactions

Science Questions	Geophysical Parameters	Measurement Requirements
How much do anthropogenic additions to natural aerosol affect the planetary energy balance via their influence on droplet and crystal nucleation? How does the aerosol influence on clouds and precipitation via nucleation depend on cloud updraft velocity and cloud type? How much does solar absorption by anthropogenic aerosol affect cloud radiative forcing and precipitation? What are the key mechanisms by which clouds process aerosols and influence the vertical profile of aerosol physical and optical properties? What are the processes that cause a polluted non-precipitating airmass to rapidly change to a clean precipitating airmass?	Vertically resolved: 1. N_a 2. $\tau_{a\text{-}abs}(\lambda)$ 3. $r_{eff,a}$ 4. N_c 5. cloud liquid water content 6. precipitation Cloud top 7. cloud top height 8. Cloud albedo 9. Cloud liquid water path 10. τ_c 11. $r_{eff,c}$ 12. cloud radiative effect Cloud base 13. cloud base height 14. updraft velocity	High Resolution Spectral Lidar (HSRL): 1, 2, 3, 10 Imaging polarimeter: 1, 2, 3 W Band Radar: 4, 5, 6, 7, 13, 14 Ka Band Radar: 4, 5, 6, 7, 13 High-Resolution VIS-SWIR Imager: 7, 9, 10, 11, 12 Wide Swath Vis-IR Imager: 9, 11 Low Freq. Microwave: 5, 6, 9, 11 High Freq. Microwave: 5, 9, 11

ACE Draft Report

Aerosol-Ocean STM

<table>
<tr><th>Category</th><th>Focused Questions</th><th>Approach</th><th>Maps to Science Question</th><th>Measurement Requirements</th><th>Instrument Requirements</th><th>Platform Requir'ts</th><th>Other Needs</th></tr>
<tr>
<td rowspan="8">Ocean-Aerosol Inter-action</td>
<td rowspan="8">1 What is the flux of aerosols to the ocean and their temporal and spatial distribution

2 What are the physical and chemical characteristics, sources, and strengths of aerosols deposited into the oceans?

3 How are the physical and chemical characteristics of deposited aerosols transformed in the atmosphere?

4 What is the spatial and temporal distribution of aerosols and gases emitted from the ocean and how are these fluxes regulated by ocean ecosystems? (Links to Ocean Ecology Question 4)

5 What are the feedbacks between ocean emissions and the microphysical and radiative properties of the overlying aerosols and clouds? How are these feedbacks changing?</td>
<td>1) Identify microphysical and optical properties of aerosols, partition natural and anthropogenic sources, and characterize spectral complex index of refraction and particle size distribution</td>
<td>2
3
5</td>
<td rowspan="4">Satellite
• Radiances & polarization at selected UV, visible and SWIR bands for aerosol types (dust, smoke, etc.), complex index of refraction, effective height, optical thickness, and size distribution with 2-day global coverage to resolve temporal evolution of plumes
• Active (lidar) measurements of aerosol properties along orbit track to refine height distribution and composition
• Drizzle detection and precipitation rates coincident with lidar & polarimeter data
• Global phytoplankton pigment absorption, dissolved organics absorption, total & phytoplankton carbon concentration, ocean particle size distribution, phytoplankton fluorescence, Chl:C, and growth rate
• Particle scattering & vertical distribution through active (lidar) subsurface returns</td>
<td rowspan="4">Spectrometer
• requirements as stated in ocean STM

Polarimeter
• requirements as stated in aerosol STM

Lidar
• requirements as in ocean STM

Duel frequency Doppler radar
• requirements as stated in cloud STM</td>
<td rowspan="8">Orbit permitting 2-day global coverage for passive radiometer & polarimeter measurements

Sun-synchronous orbit with crossing time between 10:30 a.m. & 1:30 p.m.

Storage and download of full spectral and spatial data

Monthly lunar calibration at 7° phase angle through Earth observing port

Additional platform requirements for polarimeter, lidar and radar as detailed in Ocean, Aerosol, and Cloud STMs</td>
<td rowspan="8">Supporting Global data

• Humidity profiles
• Precipitation
• Formaldehyde
• Glyoxal
• IO
• BrO
• NO_2
• SO_2

Other Data

•Ground-based aerosol observational network</td>
</tr>
<tr><td>2) Characterize dust aerosols, their column mass, iron content and other trace elements, and their regional-to-global scale transport and flux from events to the annual cycle</td><td>1
2</td></tr>
<tr><td>3) Conduct appropriate field observations to validate satellite retrievals of aerosols and ocean ecosystem features</td><td>1
4</td></tr>
<tr><td>4) Use ACE space and field observations to constrain models to evaluate (1) aerosol chemical transformations and long range transport, (2) air-to-sea and sea-to-air exchange and (3) impacts on ocean biology</td><td>2
4
5</td></tr>
<tr><td>5) Characterize aerosol chemical composition and transformation during transport (including influences of vertically distributed NO_2, SO_2, formaldehyde, glyoxal, IO, BrO) and partition gas-derived and mechanically-derived contributions to total aerosol column</td><td>2
3
4</td>
<td colspan="2" rowspan="2">Supporting Field & Laboratory Measurements
• Dust chemical properties/solubility/ chemical transformation
• Aerosol optical properties, heights, chemical composition, and partitioning of gas-derived and mechanically-derived contributions to total column load
• DMS flux and dissolved concentration and precursors
• Atmospheric boundary layer trace gases, NO_2 / SO_2 height distribution
• Diffuse irradiance and in-water optics
• Surface layer plankton species, phytoplankton carbon, fluorescence
• Observational network representative of global range in properties
• Process/mechanism oriented field and laboratory studies
• Sustain time series field measurements of key properties over active lifetime of mission</td></tr>
<tr><td>6) Monitor global phytoplankton biomass, pigments, taxonomic groups, productivity, Chl:C, and fluorescence; measure and distinguish ocean particle pools and colored dissolved organic material; quantify aerosol-relevant surface ocean photobiological and photobiochemical processes</td><td>4
5</td></tr>
<tr><td>7) Relate changes in ocean biology/emissions to aerosol deposition patterns and events</td><td>3
4</td>
<td colspan="2" rowspan="2">Modeling
• Conduct model tracer studies to determine sources, composition, and chemical attributes of aerosols
• Model height distribution of NO_2 & SO_2 and dust chemistry
• Use satellite data to constrain model aerosol source strengths
• Model air-sea exchange rates and temporal variability, including sources of aerosols to atmosphere
• Run coupled ocean biogeochemistry model to assess impacts and compare to observed response of ocean ecosystems</td></tr>
<tr><td>8) Demonstrate influences of ocean taxonomy, physiological stress, and photochemistry on cloud/aerosol properties, including organic aerosol transfer</td><td>1
2
3</td></tr>
</table>

ACE Aerosol Retrieval Parameters Not Achievable with Threshold PACE (OCI) mission (from PACE SDT Report)

Table 2-2. ACE aerosol retrieval parameters not achievable with the atmosphere threshold PACE mission.

Category / Instrument	Parameter (from ACE STM*)	Example Science and Applications
3M Sensor	Aerosol type (particle size distribution, shape, SSA, complex refractive index, constraints over land and water)	Aerosol Direct Radiative Forcing and Its Anthropogenic Component; Aerosol Indirect Effect and Its Anthropogenic Component; Aerosol Transport Mods; Aerosol Source Attribution; Aerosol Particle Evolution; Improving AOD Retrieval Accuracy Characterization of Stratospheric Aerosols
3M Sensor	Aerosol plume height	Aerosol Transport Modeling; Aerosol Plume Evolution; Wildfire and Volcano Plume Injection Energetics and Hazard Assessment
HSRL	Multiple-layer aerosol vertical distribution	Aerosol Direct Radiative Forcing; Aerosol Transport Modeling; Aerosol Type Retrieval
HSRL	Layer-resolved aerosol type	Aerosol Direct Radiative Forcing; Aerosol Source Attribution; Air Quality Assessment for human health
HSRL	Near-cloud aerosol amount and type	Aerosol Direct Radiative Forcing; Aerosol Indirect Forcing; Aerosol-cloud processing;

*** These instrument capabilities are based on the draft ACE Science Definition Team report.**

3MI Specifications (from PACE SDT Report)

Table 2-3. Current* 3MI specifications. λ = central band wavelength (µm). FWHM = Full Width at Half Maximum (µm). Lref = Reference TOA clear sky radiance (W m^{-2} sr^{-1} μm^{-1}). SNR = Signal to Noise Ratio.

λ	FWHM	Polarization †	NEΔL @ L_{ref}	SNR§	Primary Use
0.410	0.02	Yes	0.23	200	Absorbing aerosol
0.443	0.02	Yes	0.28	200	Aerosol absorption and height indicators
0.490	0.02	Yes	0.29	200	Aerosol, surface albedo, cloud reflectance, cloud optical depth
0.555	0.02	Yes	0.28	200	Surface albedo
0.670	0.02	Yes	0.22	200	Aerosol properties
0.763	0.01	No	0.18	200	Cloud and aerosol height
0.754	0.02	No	0.18	200	Cloud and aerosol height
0.865	0.04	Yes	0.14	200	Vegetation, aerosol, clouds, surface features
0.910	0.02	No	0.13	200	Water vapor, atmospheric correction
1.370	0.04	Yes	0.05	200	Cirrus clouds, water vapor imagery,
1.650	0.04	Yes	0.03	200	Ground characterization for aerosol inversion
2.130	0.04	Yes	0.01	200	Cloud microphysics at cloud top, Vegetation, fire (effects) Ground characterization for aerosol inversion

† Estimated uncertainty in degree of linear polarization: 1%

§ Nadir pixel size: 4 km

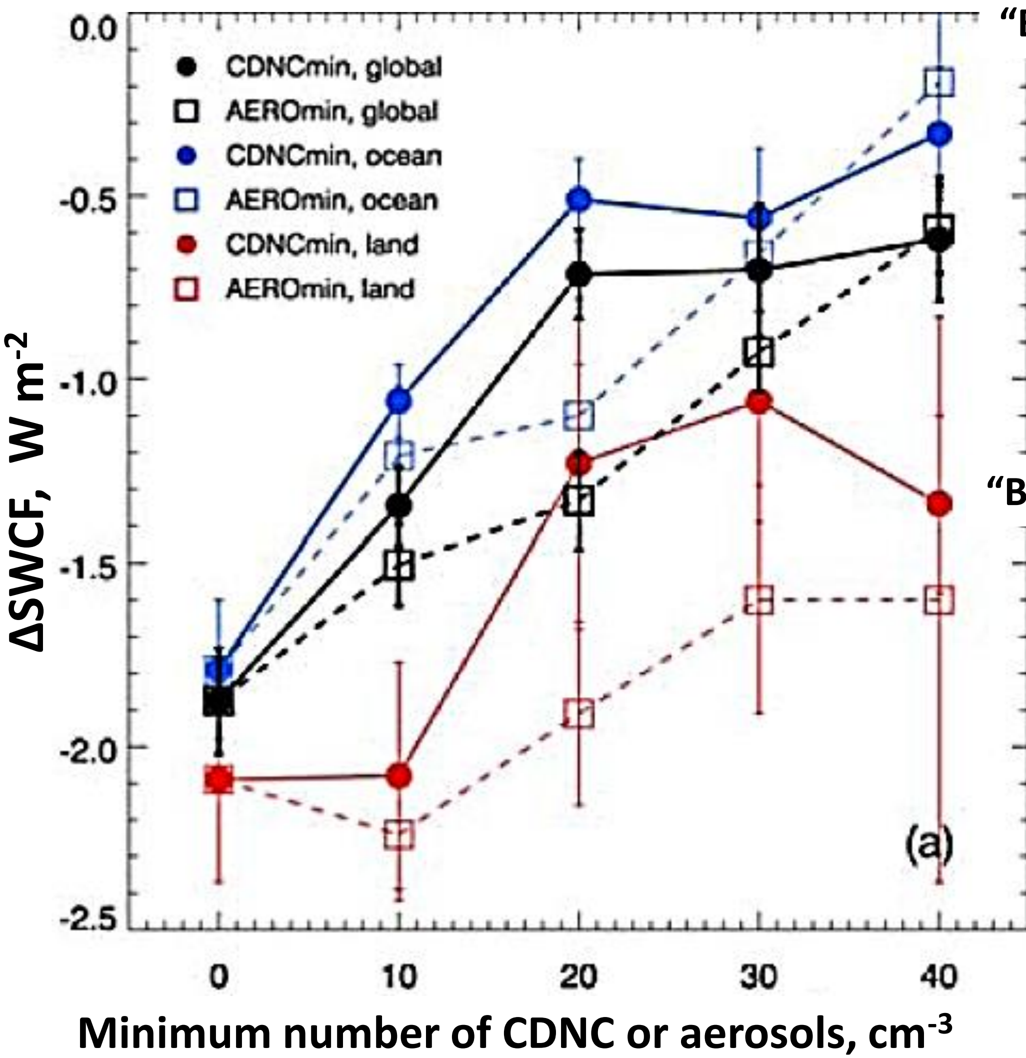
*** Latest 3MI specifications can be obtained from Eumetsat through the EPS-SG resources website: http://www.eumetsat.int/Home/Main/Satellites/EPS-SG/Resources/index.htm?l=en**

Aerosol – Ocean Ecosystems

Importance of Marine Ecosystem for Anthropogenic Climate Forcing Assessments

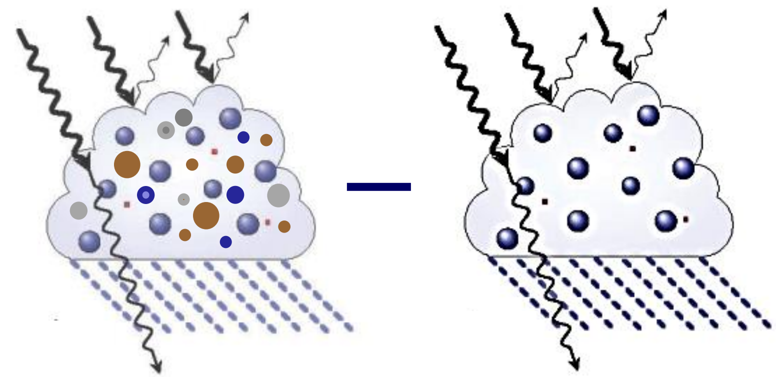
- Current GCMs poorly quantify fluxes of marine primary aerosols and ocean biologically generated reactive gases
- Correct assessments of aerosol number concentration and size distribution over pristine marine regions may have profound effect on **model predicted extent of human-induced climate change**
- One of the *tuning* knobs in the models

Difference in Short-wave Cloud Forcing (SWCF)

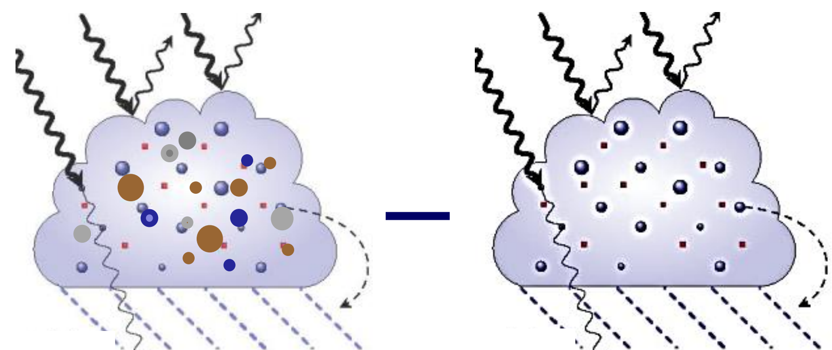


[Source: Hoose et al., 2009]

"Background" CCN or CDNC ~10 to 20 cm^{-3}



"Background" CCN or CDNC ~30 to 40 cm^{-3}



- Improving *Ocean-Aerosol Interaction* will go a long way toward narrowing uncertainty in aerosol indirect effect
- Will also help reconcile the differences between the model predictions and satellite estimates/inverse calculations

What are the physiochemical characteristics, temporal and spatial distributions, and source of aerosols deposited in oceans?

- A-Train+Terra+suborbital observations today
  - Allow us to identify aerosol types, vertical distribution, sources, and transport but with large quantitative uncertainty
  - Provide vertical distribution of aerosol extinction, but cannot provide detailed aerosol properties (size, shape)
  - Cannot provide detailed aerosol physical and optical properties
- ACE (polarimeter+HSRL+ocean color hyperspectral imager)
  - Provide direct observations of extinction
  - Allow for quantitative identification of vertical distribution of aerosol type
  - Provide quantitative information about aerosol optical and microphysical properties

What is number concentration, size distribution, chemical composition, and CCN properties of sea spray aerosols?

- A-Train+Terra+suborbital observations today
  - Provide a proxy for aerosol number concentration in atmospheric column, but cannot provide the number concentration itself or the information on vertical distribution
  - Provide columnar CCN concentration over the ocean, but with crude assumptions of i) all aerosols smaller than dry diameter <0.5 µm will activate and become cloud droplets, and ii) all aerosols are evenly distributed in a column
  - Prescribes size distribution and optical properties without explicit identification of particle type
- ACE (polarimeter+HSRL+ocean color hyperspectral imager)
  - Locate, characterize and quantify point sources (fires, dust, large ocean blooms)
  - Provide quantitative vertical layer-resolved information about aerosol optical and microphysical properties for aerosol number concentration, absorption, and size

How do ocean ecosystems respond to aerosol deposition? How do megacities affect coastal ecology?

- A-Train+Terra+suborbital observations today
  - Provide information on surface Chlorophyll A concentration and carbon stock, but not physiological state of phytoplankton
  - Can provide valuable information on phytoplankton biomass and total particulate organic carbon sticks with day-night sampling, and observations through absorbing aerosols and thin cloud layers, but with poor vertical resolution through the water column
- ACE (polarimeter+HSRL+ocean color hyperspectral imager)
  - Improved spectral resolution in the UV and visible region allow retrievals of phytoplankton carbon and physiology
  - Improved vertical resolution and effective separation of particulate and Brillouin scattering components could yield three-dimensional global reconstruction of upper ocean plankton ecosystems
  - Key properties of optically complex coastal inland waters can be retrieved near the red edge of pigment absorption (near infrared)

Aerosol Indirect Effects

Effect	Cloud type	Description	F_{TOA}	F_{SFC}	P
Indirect aerosol effect for clouds with fixed water amounts (cloud albedo or Twomey effect)	All clouds	The more numerous smaller cloud particles reflect more solar radiation	-0.5 to -1.9	similar to F_{TOA}	n/a
Indirect aerosol effect with varying water amounts (cloud lifetime effect)	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	-0.3 to -1.4	similar to F_{TOA}	decrease
Semi-direct effect	All clouds	Absorption of solar radiation by soot may cause evaporation of cloud particles	$+0.1$ to -0.5	larger than F_{TOA}	decrease
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay the onset of freezing	?	?	increase or decrease
Glaciation indirect effect	Mixed-phase clouds	More ice nuclei increase the precipitation efficiency	?	?	increase
Riming indirect effect	Mixed-phase clouds	Smaller cloud droplets decrease the riming efficiency	?	?	decrease
Surface energy budget effect	All clouds	Increased aerosol and cloud optical thickness decrease the net surface solar radiation	n/a	-1.8 to -4	decrease

Lohmann and Feichter, 2005